

MODELING AND FINITE ELEMENT ANALYSIS OF VERTICAL AXIS WIND TURBINE ROTOR CONFIGURATIONS

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ABSTRACT

This paper deals with the modeling and analysis of vertical axis wind turbine rotors (Savinious rotor; H rotor and their hybrid). Analysis includes stress and deformation distribution on rotors of different materials (Steel alloy, Aluminium alloy and Carbon Fibre Composite). Stress and deformation depend on the type of rotor and density of material.

KEYWORDS: Vertical Axis Wind Turbine, Mechanical Stress, Geometric Modeling, FEM, Rotor Configurations

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INTRODUCTION

The wind turbine industry has experienced a huge development in the last 20 years. Wind turbine sizes have grown since then from 0.5 kW to 4.5MW. This growth is possible because of some scientific and product development strategies that are assisted by powerful computers and new software-tools.

The paper aims to do the comparative stress and deformation analysis of various Vertical Axis Wind Rotors and their hybrid configurations using Finite Element Analysis. In this work the modeling is done using Pro/E and the FEM analysis is done on Ansys.

VERTICAL AXIS WIND TURBINE

Considering the rotor axis position wind turbine can be classified as: Vertical axis wind turbine (VAWT) and horizontal axis wind turbine(HAWT).

Vertical Axis Wind Rotor [1] is known as cross wind axis machine. Here the axis of rotation is perpendicular to the direction of the wind and to the ground.

The main advantages of the vertical wind turbine are

- It accepts the wind from any direction
- Permits mounting of generator and gear box at the ground level
- VAWT require small working space so it can be mounted on the house roofs.
- Following are the disadvantages of a vertical wind turbine;
- Requires guy wires attached to the top for support, which may limit its application, particularly for

offshore sites

- Has lesser efficiency value.

Based on the applications the following are the commonly used;

- Savonious Rotor
- H rotor
- Darrius Rotor

This paper deals with the analysis of Savonious rotor and H rotor.

HYBRID VERTICAL AXIS WIND ROTORS

A hybrid wind Rotor [2, 3] refers to the combination of two rotors on a single shaft. A combined rotor has better efficiency and high starting torque as compared to individual rotor.

Present study is for the hybrid configurations of Savonious-H rotor.

LITERATURE REVIEW

The vertical axis wind rotors Savonious [1] and Darrius [1] are often studied by many researchers. Most of them worked for improving the performance of the wind rotor, experimentally. Whereas the other factors such as stress and deformation produced in the material due to different loads acting on the wind rotor is not given much attention. The finite element analysis is mainly done for horizontal axis wind turbine by some manufacturers and few researchers. Performance improvement [3,4] has been attempted for hybrid rotors. R. Gupta et al. [2] studied the performance of Savonious rotor as well as Savonious-Darrius machine, experimentally. Two types of models, one Savonious rotor and other Savonious-Darrius machine were designed and fabricated and tested in subsonic wind tunnel. It was observed that there was improvement in the power coefficient for Savonious-Darrius machine compared to Savonious rotor under similar test conditions. Similarly, experimental work on Darrius rotor combined with the Savonious model was undertaken by Ali [6] in which theoretical results of the combined machine have been compared with the experimental results. The comparison shows a very good agreement between the two. As far as known no work is available for stress and deformation analysis of hybrid rotors.

In the present work, a comparative analysis of Savonious rotor, H- rotor and the combination of two has been done.

MATHEMATICAL ANALYSIS OF VAWT

- Power Available in the Wind[5]

$$P = 0.5 \rho C_p V^3 A \eta_m \eta_e$$

P= power Available in the wind ρ = density of air

η_e = Electrical efficiency

η_m = mechanical efficiency

V = wind speed

A = Swept area of rotor

C_p = Coefficient of performance

- **Swept Area of the Rotor [5]**

- Savonius rotor

The area of Savonius Rotor is given by

$$A = H.D$$

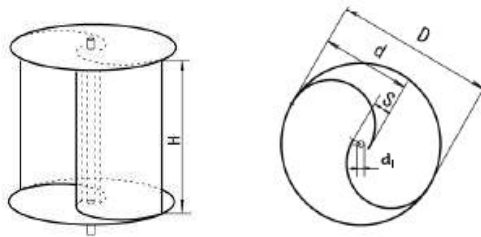


Figure 1: Savonius Rotor

Where,

H = height of Savonius rotor; d = diameter of cup

D = diameter of Savonius profile; d_1 = shaft diameter; S is the overlap.

- H Rotor

The area of H- Rotor [5] is given by

$$A = DH$$

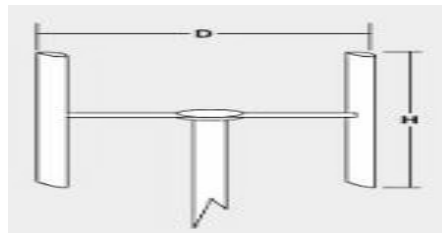


Figure 2: H Rotor

- **Torque Calculation**

$$T = F * R$$

T is the torque produced due to the force of the wind

F is the force acting; R is Radius of rotor

Also,

The torque acting can be calculated as

$$T = \frac{P}{\omega}$$

where, P is the output power and ω is the angular velocity is given as follows.

$$\omega = \frac{2\pi n}{60}$$

Where n is the rotational speed in rpm.

By substituting these values, we get,

$$T = 9.55 \cdot \frac{P}{n} \text{ N-m}$$

Where P is in kilowatts (kW)

$$\text{i.e. } T = 9.55 \times 10^3 \frac{P}{n} \text{ N-mm; Where P is in kilowatts (kW)}$$

- **Calculation of Rotational Speed**

$$V = R\omega \quad \text{And} \quad \omega = \frac{2\pi n}{60}$$

From here we get

$$n = \frac{60 V}{\pi 2R}$$

Where V is the peripheral velocity of the rotor and is equal to the velocity of the win

- **Calculation for Hybrid Rotor**

Force acting on the blades and the torque produced are calculated with an assumption that the total power output (shaft) is contributed equally by both the rotors using all the above relations

ASSUMPTIONS

The various assumptions for modeling and analysis are stated below:

- The power output of all the wind rotors are same (here for analysis power output is taken as 1.1 KW)
- The Speed of the wind is same for all the rotors (here 15 m/s for analysis)
- The coefficient of performance i.e. C_p is taken as 0.3
- Mechanical and electrical efficiency is taken as 0.90 and 0.95 respectively.
- The diameter of all rotors is constant and taken as 1 meter; only their height is changed to fulfill the requirement of calculating swept area.
- The torque acting on all the rotors is same and so is the rotational speed.
- The forces acting on the rotors due to wind are same but this force is acting on different shapes of wind rotor1s,

therefore the same wind force along with the gravitational force will produce different stress for different shapes and so as the deformation.

- The width thickness of the blade is takes as 3 mm.

The values of different parameters are taken on the basis of the work carried out by previous researchers.

GEOMETRIC MODELING

The modeling of the different wind rotors is done according to the dimensions calculated

Actual power available in the wind is

$$P = 0.5 \rho V^3 A C_p \eta_m \eta_g$$

Here, $P=1.1\text{KW}$, $C_p=0.3$, $V=15\text{ m/sec}$, $\eta_m=0.95$,

$\eta_g=0.90$, $\rho=1.2255\text{ Kg/m}^3$

Putting these values in the above equations

$$1100 = 0.5 * 1.225 * 15^3 * A * 0.3 * 0.90 * 0.95$$

$$1100 = 530.233 A$$

$$A = 2.07\text{ m}^2$$

From these, the dimensions of rotor is calculated, as following,

For Savonius Rotor

$$A = D.H$$

A = calculated swept area and $D=1\text{ meter}$ and H = height of rotor

Therefore

$$H = 2.07\text{ meter i.e. } 2070\text{ mm}$$

And the cup diameter is $D/2$ i.e. 500 mm since there is no overlap.

For H –Rotor

$$D = 1000\text{ and } H = 2070$$

But here the diameter D is composed of following

$$D = 2(L+r)$$

$$\text{Here } r = 80\text{ mm}$$

$$\text{Therefore } L = 420$$

For Hybrid Rotors

The calculation is done in the similar manner as that of the above and then the Rotors are combined one over other to get the hybrid structure.

The power in this case will be half of the total power

$$550 = 0.5 * 1.225 * 15^3 * A * 0.3 * 0.90 * 0.95$$

$$550 = 530.233 A$$

$$A = 1.037 \text{ m}^2$$

From this the dimension of hybrid rotor can be calculated

Savonious Rotor

$$D = 1000 \text{ mm and } H = 1037 \text{ mm}$$

H rotor

$$D = 1000 \text{ mm and } H = 1037$$

Length of the shaft is taken according to the height of the rotor. With these, dimension modeling of the different rotors is done and then it is sends to ANSYS software for Finite Element Analysis.

LOADS CALCULATION

There are two major loads that are taken into consideration for the analysis:

- Load due to gravity
- Load of forces due to wind

The load due to gravity depends upon the mass of the structure and acts in downward direction. It can be easily be calculated from

$$F_g = m * g$$

where F_g is the weight of the body is the mass of the structure and g is the acceleration due to gravity.

The wind force is calculated as following:

- **The Rotational Speed of the Rotor is given by;**

$$n = \frac{60 V}{\pi 2R}$$

Here V is the wind speed in mm/sec, and R is the rotor radius in mm

$$n = (60.15000) / (3.14 * 2 * 500)$$

$$n = 286.62$$

$$n = 287 \text{ RPM}$$

- **The Torque is given by;**

$$T = 9.55 \times 10^6 \frac{P}{R}$$

$$T = 9.55 * 10^6 * (1.1/287)$$

$$T = 36602.78 \text{ N-mm}$$

- **The Force Acting on the Blades is given by;**

$$F = T/R$$

$$F = 36602.78 / (500)$$

$$F = 73.21 \text{ N}$$

For hybrid rotors, since the power is half and all the other factors are same, such as rotor diameter, the force acting on hybrid rotors is

$$F = 73.21 / 2$$

$$= 36.60 \text{ N}$$

MATERIALS USED

Following three materials have been considered for this study;

- **Plain Carbon Low Alloy Steel**

The material used for the analysis is Plain Carbon Low Alloy Steel [7] (A36 having composition of Fe- 98%, Mn-1.0 %, C-0.29%, Si-0.28)

- **Aluminum Alloy**

Aluminum Alloy [7] 6061 with chemical composition of 95.85% Al, 1.0 % Mg, 0.6% Si, 0.3 % Cu, and 0.20% Cr

- **Carbon Fiber**

Carbon Fiber Composite Material (Unidirectional Fiber/Epoxy Matrix) is taken for the analysis.

FINITE ELEMENT MODELLING

The following figure shows the various constraints acting on the Savonious rotor:

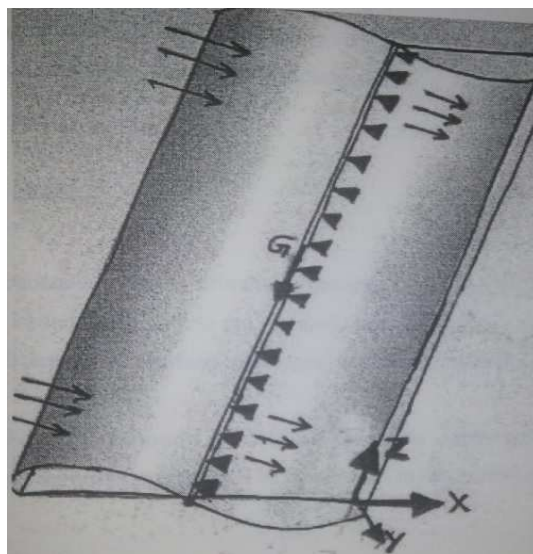


Figure 3: Boundary Conditions Acting on Savonious Rotor

U_x =Deformation in X Direction, U_y =Deformation in Y Direction, U_z =Deformation in Z Direction.

Wind Load in Y Direction, Gravity Load in Z Direction

DISCUSSION OF RESULTS

Finite Element analysis has been done to obtain deformation and stress distribution in rotors.

- **Deformation**

Figures 4, 5 & 6 show the deformation distribution in different rotors using stainless steel as material.

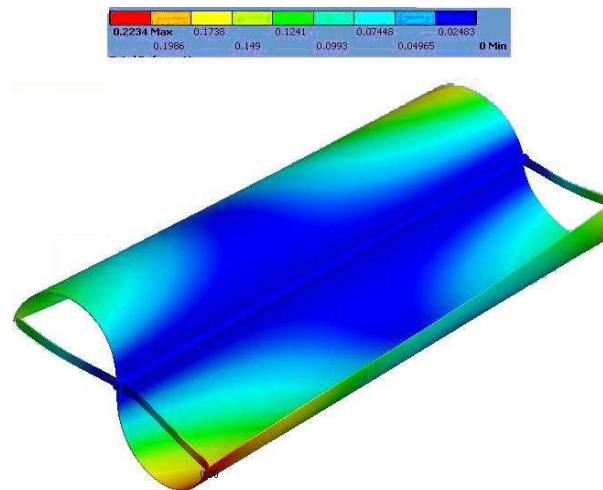


Figure 4: Deformation in Savonius Rotor

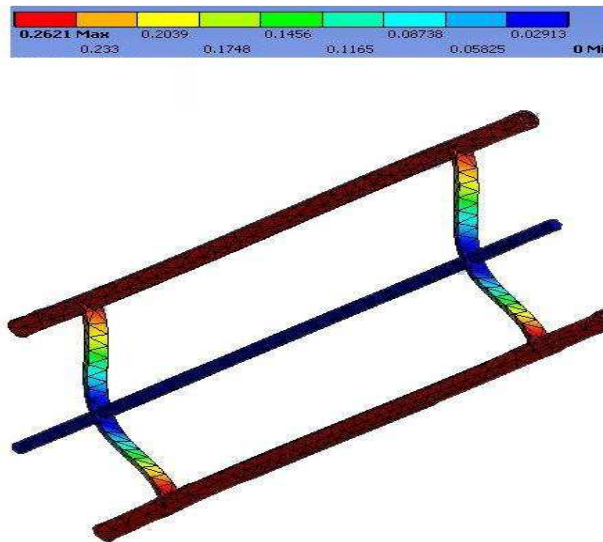


Figure 5: Deformation in H Rotor

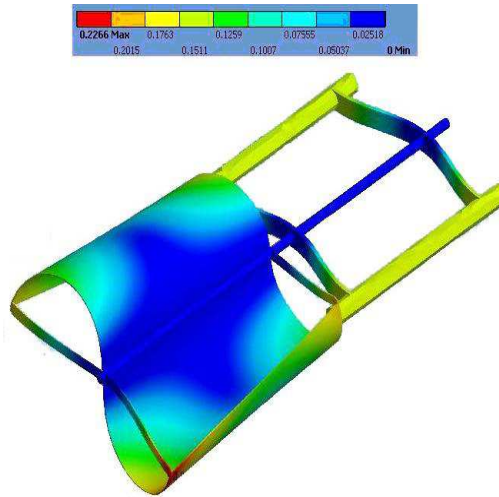


Figure 6: Deformation in Hybrid Rotor

- **Stress Distribution**

The Equivalent stress acting on the model is plotted when stress display is required. The Von Mises stress for checking yield stress is chosen.

The stress generated in various individual and hybrid rotor is shown in figures 7, 8 & 9.

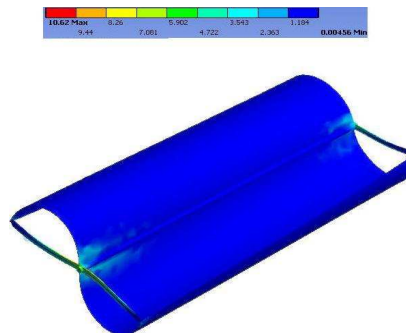


Figure 7: Stress in Savonius Rotor

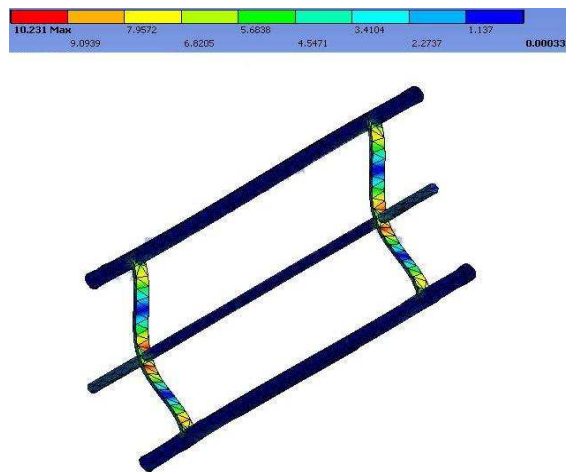


Figure 8: Stress in H Rotor

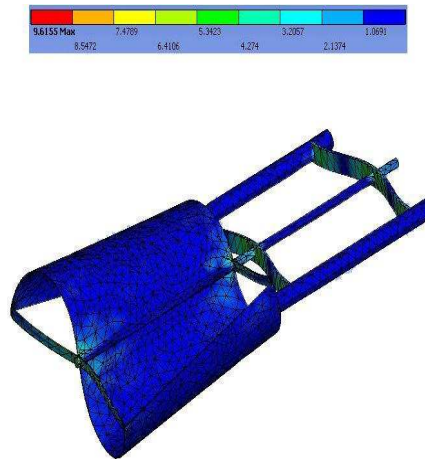


Figure 9: Stress in Hybrid Rotor

Similarly stress and deformation analysis was carried out using aluminum alloy and carbon fiber as material. The result of mass, deformation and stress for different material is tabulated (Tables 1, 2 & 3) and also depicted by graphically in figures 10, 11 & 12.

Table 1: Mass of Rotors

	Mass(Kg)		
	S. Steel	Al Alloy	Carbon Fiber
Savonious	146.74	52.447	30.294
H Rotor	120.23	42.971	24.821
Savonious H rotor	136.74	48.873	28.23

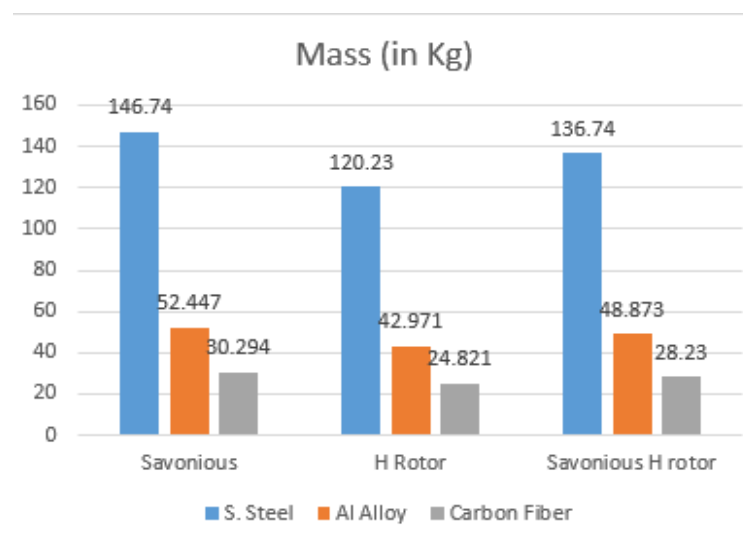
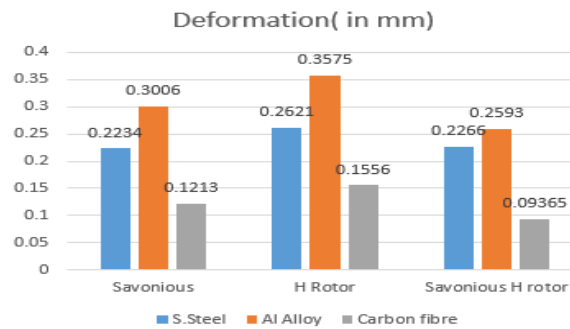


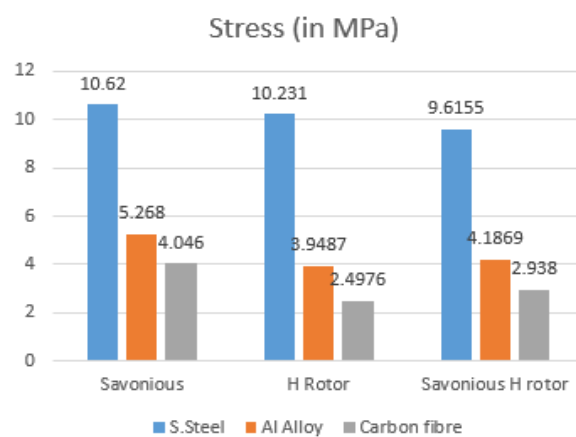
Figure 10: Mass of Rotors

Table 2: Deformation in Various Rotors

	Deformation(mm)		
	S. Steel	Al alloy	Carbon Fiber
Savonious	0.2234	0.3006	0.1213
H Rotor	0.2621	0.3575	0.1556
Savonious H rotor	0.2266	0.2593	0.09365

**Figure 11: Deformation in Various Rotors****Table 3: Stress in Various Rotors**

	Stress (MPa)		
	S. Steel	Al alloy	Carbon Fiber
Savonious	10.62	5.268	4.046
H Rotor	10.231	3.9487	2.4976
Savonious H rotor	9.6155	4.1869	2.938

**Figure 12: Stress in various rotor**

CONCLUSIONS

On the basis of the above modeling and analysis, following conclusions are made:

- Maximum deformation is produced in H Rotor and minimum in Savonious rotor, when the material used is Steel alloy.

When material used is Aluminium alloy, the maximum deformation is produced in H- Rotor and minimum in Savonious-H rotor.

Whereas, in the case of Carbon Fibre Composite, the maximum deformation is produced in H- Rotor, and the minimum in Savonious – H Rotor.

- The maximum stress is produced in Savonious Rotor and minimum in Savonious-H-Rotor, when the material used is Steel alloy.

In case of Aluminium alloy, The maximum stress is produced in Savonious Rotor and minimum in H Rotor.

Similarly when for Carbon Fiber Composite, the maximum stress is produced in Savonious Rotor and minimum in H Rotor.

One thing is worth noting, that both, the deformation and stress values varies drastically with the density of the material. The material with less density shows minimum deformation and stress.

Thus on the basis of this analysis if deformation is criteria then hybrid configuration of Savonious-H rotor made of Carbon fiber show least deformation.

On the other hand, when stress is design criteria H-rotor made of carbon fiber shows minimum induced stress.

The present work is based on the maximum value of stress and deformation as calculated by ANSYS software that generates an approximate solution. So some analytical or experimental method should be developed for calculating exact values of stress and deformation. Also, materials having less density and good strength can be tried for the same analysis.

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